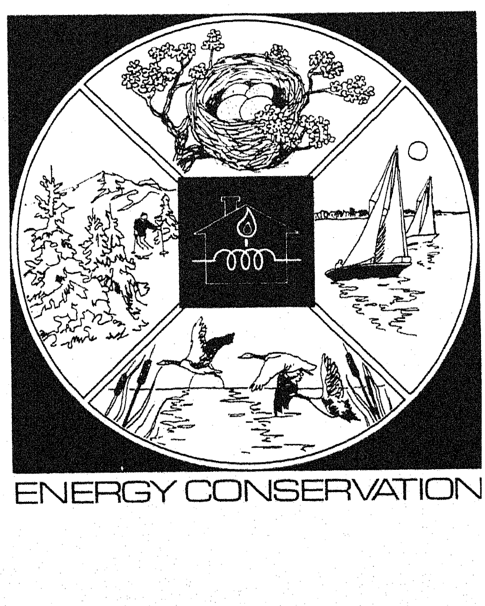
RESIDENTIAL ENERGY CONSUMPTION

VERIFICATION OF THE TIME-RESPONSE METHOD FOR HEAT LOAD CALCULATION

August 1973

Department of Housing and Urban Development

Office of the Assistant Secretary for Policy Development and Research



ENERGY CONSERVATION

Report No. HUD-HAI-5

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I. SUMMARY AND CONCLUSIONS

A study was performed to evaluate the validity of the "time-response" method for calculating hourly and long term heat load requirements of occupied single-family residences. Selected for this study was a two-story detached single-family residence using construction methods and materials typical to the Mid-Atlantic section of the country. Heat load values based on the thermal parameters of the structure, actual weather data and estimated internal load profiles were calculated and compared with the heat loads measured in three occupied residences. Additional heating requirement data from a larger sample of residences were evaluated to measure the actual range of heat requirements that could be expected for a given style of house and, if possible, to correlate observed differences in heating requirements with structural or occupant related variables.

The primary conclusion drawn from this study was that the "time-response" method for calculating heat load requirements provides a reasonably accurate method for calculating hourly and long term heat loads for houses exhibiting average consumption patterns. Whereas the calculated and measured heat load values for a 34-day test period were within 10 percent, the limits of accuracy of the calculated value cannot be established without further testing. To better define the accuracy limits of the calculation methods, additional data would be required on heating system efficiency, uniformity and quality of structural components and on the limits of occupant lifestyle factors.

Total house heat losses (and related heat loads) calculated by the "degree-day" method were 16 to 40 percent greater* than those calculated by the "time-response" method.

Hourly variations in heat loads were generally related to variations in air infiltration rates. For the test period, calculations showed that infiltrated air accounted for 28 percent of the house's heat losses. These results provide qualitative validation of the air infiltration model and highlight the strong relationships between air infiltration and heat load.

The demonstrated ability of the "time-response" method to predict heat load requirements of average** occupied residences, provides validation of the methods of analyses used for the evaluation of energy conservative modification reported in reference (1).

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* For "degree-day" baselines of 65° and 72°F.

** Residences having average combinations of occupant lifestyle and construction quality.

II. BACKGROUND

As part of an earlier work, the "time-response" method for calculating heating and cooling requirements was adopted for single-family residences. (1) This method of calculation treated the total house structure as a thermal system acted upon by internal loads (occupants, lights and appliances) and by the weather and solar loads. Since the internal and external factors are ever-changing parameters (hourly, daily, and seasonally), annual heating and cooling requirements were determined by summation of hourly requirements. For calculation of the heating (or cooling) load of a particular residence, the internal load factors were adjusted to allow for differences in number and use rate of lights and appliances, number of occupants and estimates of lifestyle factors. Such adjustments were made by estimating typical 24-hour profiles for appliance load, light load and occupancy. External load factors are determined from actual hourly weather and solar data. It was the objective of this study to compare the heat load requirements of a single-family residence as calculated by the time response method with measured heat load data, and to analyze the results to obtain a measure of the validity of the various assumptions and of the overall method.

The single-family residence selected for this study was "The Trent" house, as constructed at the Twin Rivers Planned Unit Development, Twin Rivers, New Jersey. The selection of this particular house and site was based on the following considerations:

(1) "The Trent" house was typical of the style and quality of new single-family residences constructed in the Mid-Atlantic section of the country.

(2) "The Trent" house was a near-perfect match of the plan, construction type and materials, and "lifestyle" factors identified for the "Characteristic House", used as a baseline in the analyses of the energy consumption in single-family residences (1).

(3) Princeton University's Center for Environmental Studies is currently evaluating residential energy consumption patterns at the Twin Rivers site at both the micro- and macrolevels. A discussion of their overall program is given in (2).

III. EXPERIMENTAL APPROACH

The study was divided into two tasks: the experimental task wherein Princeton University obtained field data on residential energy consumption, and the analytical task wherein Hittman Associates thermally modeled and calculated the heating requirements of the house. Since this was the first attempt to evaluate the thermal model against a house under actual living conditions, the experimental task was limited to measuring only gross energy inputs to the house. The results of this preliminary study would illuminate areas requiring more detailed experimental measurement and would provide guidelines for designing similar experiments in the future.

Three occupied "The Trent" houses were selected for measurement of their energy consumption patterns over a 30-day period in the February-March 1973 heating season. The three houses, identified as A, B, and C, wererwithin one-eighth of a mile of each other and were all oriented with their long dimension east to west; houses A and B faced west, and C, east. The houses were essentially fully exposed to direct wind and sunlight. House C was the only house equipped with storm windows. Table I lists details concerning structure,

Since the furnace was the only gas consuming device in the houses, measurements of the gross energy required for heating the houses over the test period were obtained from gas meter readings. Measurements of hourly energy consumption of the furnaces were obtained by the use of strip chart recorders that indicated furnace "on-time" on a real-time basis. The on-time data were converted to hourly energy consumption by multiplying the on-time by the furnace energy input rating (108,000 Btu/hr). The consumption of the furnace pilot lights was included within the gross consumption values.*

Measurements of the gross electrical consumptions for the test period were obtained from readings of the respective electric meters at the beginning and end of the test period. To separate the consumption of the hot water heaters, strip chart recorders were used to record heating element on-time. Power consumption of the hot water heaters was then calculated using the name-plate rating of the heating elements.

Hourly weather data wereobtained during the test period from Princeton's onsite weather station; the weather station was within a quarter of a mile of the test houses. The hourly weather data included average dry and wet bulb temperature, average wind velocity and direction, precipitation and cloud cover.

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* The gas consumption of the furnace pilot lights was one cubic foot per hour. Assuming a heat value of 1000 Btu/cubic foot of gas, the pilot light consumed 1000 Btu/hr.

TABLE I. CHARACTERISTICS OF "THE TRENT" HOUSE, TWIN RIVERS, NEW JERSEY

	House A	House B	House C
House Style		Two story - 4 bedrooms	
Basement		Full	
Garage		Single car, attached	
Floor Area (living area)		1646 Sq. ft.	
Exterior Wall Construction		1/2-inch exterior plywood sheathing, 2¼-inch fiber-glass batting between studding, 1/2-inch exterior dry wall	
Ceiling Insulation		3 inches Fiberglass batting	
Roof		Ashpalt Shingles	
Window			
Type		Aluminum, single hung	
Glazing		Single	
Area		222 Sq. ft.	
Storm Windows	No	No	Yes
Patio Doors			
Type		Aluminum	
Glazing	Single	Single	Double
Area		80 Sq. ft.	
Heating System		Gas fired, forced hot air	
Humidifier	Yes	No	Yes
Occupants			
Adults	2	2	2
Children	2	2	1

During the test period, the residents were requested to keep their thermostats at their normal set-point. The residents were also requested to twice daily record the inside temperature and relative humidity in their living room, using instruments precalibrated by Princeton. No other requests or constraints were imposed on the residents.

The hourly heating requirements for "The Trent" house were calculated, using the thermal modeling and computation programs reported in reference 1. Factors considered in determining the heating requirements included thermal properties of the structure, hourly weather and solar data, and assumed hourly profiles for internal loads resulting from appliances, lights and occupants. The daily internal load profiles, assumed occupants, appliances and lights, are shown in Figure 1. The appliance and light internal loads were adjusted to correspond to the measured average daily electrical consumption of the houses. The definition of lifestyle factors was based on judgments of typical values for "The Trent" house under normal living conditions. For purposes of calculations the three houses were assumed to be identical in terms of structure and occupant lifestyle. For the computation and summation of the hourly heat loads the Residential Infiltration Program and the Residential Energy Analysis Programs were used.

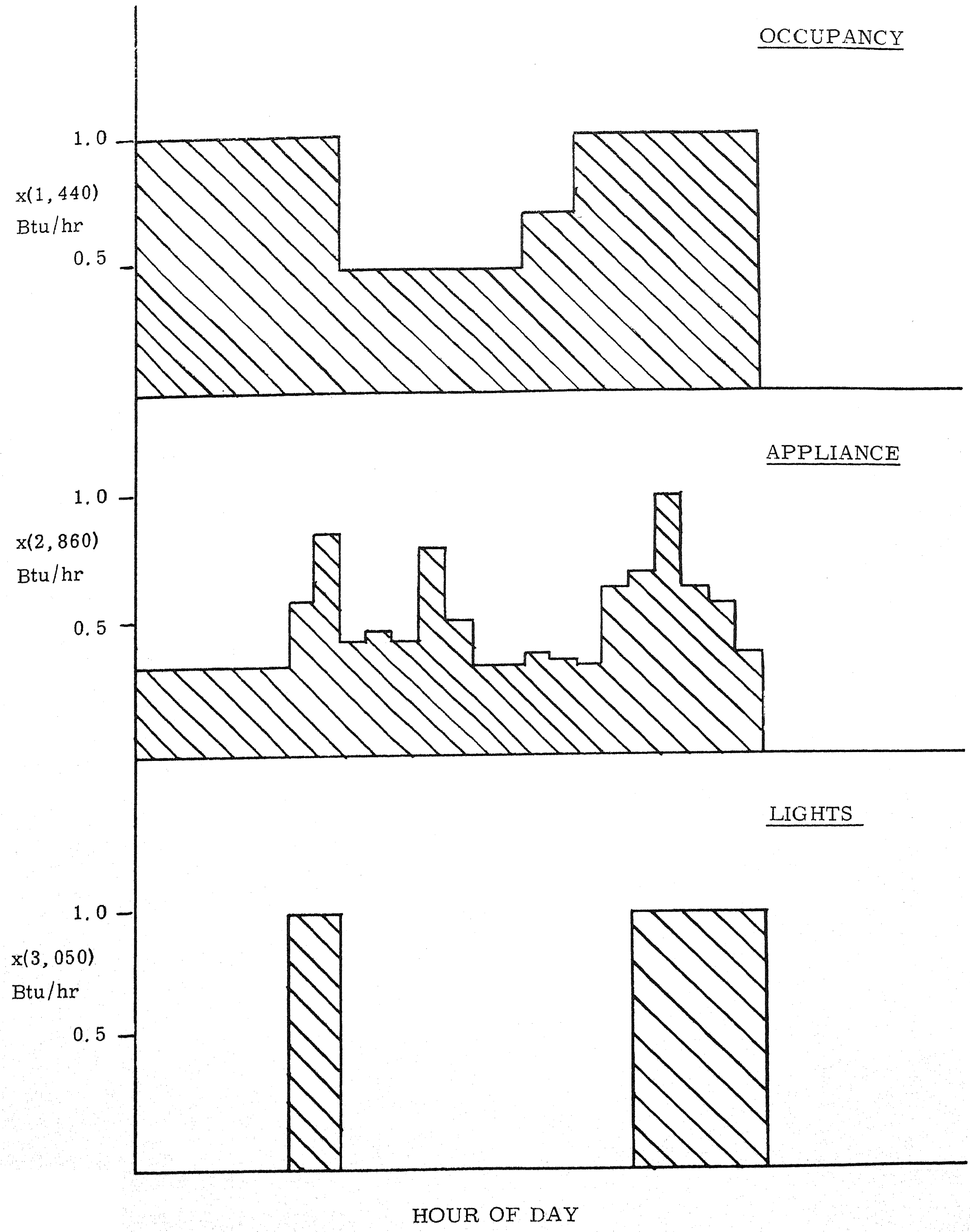

Figure 1. Assumed Daily Internal Load Profiles

IV. EXPERIMENTAL RESULTS

The measured and calculated heat loads for the February 8 - March 14, 1973 test period are given in Table II. There were no data available as to the overall efficiency of the heating systems* of the test houses, consequently a value of 0.6 was assumed as a reasonable value for a recently constructed house. As shown in Table II, the calculated values for heat load were in good agreement with the measured values adjusted for the 0.6 system efficiency. The twice-daily samplings of temperature and relative humidity in the respective living rooms are given in Table III. The average room temperature of House A was 75°F and for Houses B and C, 71°F. For the calculation of the heat loads, a uniform house temperature of 72°F was selected and a constant relative humidity of 40 percent was assumed. The data in Table III shows that the assumed value was a good estimate of average relative humidity during the test period.

As indicated in Table I, Houses A and C had automatic humidifiers installed but House B did not. Examination of the humidity data in Table II shows that if the humidity data points of House A were adjusted for an average temperature of 71°F, the relative humidities in the three houses would be approximately similar. These data suggest that humidification was not required during this test period, and that the furnace did not have to meet the latent load for humidification. The thermal model allowed for humidification, if required, to meet the 40 percent relative humidity set point, and included any associated latent load in the total calculated heat load. In the calculation of heat loads, no humidification (latent load) was required during the test period.

The calculated values of heat loss associated with the various components of the house structure are given in Table IV. Also given in this table are the heat losses as calculated by the "degree-day" method recommended by American Society of Heating, Refrigeration and Air Conditioning Engineers (3). The total heat loss calculated by the degree-day method using a 65° and 72°F baseline temperature were 16 percent and 40 percent greater respectively than the value calculated by the time reponse method. Comparison of the calculated heat losses through the various structural components showed that the time-response values were greater for the walls, but lower for the windows, doors, ceiling, floor, and infiltration.

Although hourly energy consumption data was monitored at the three houses during the test period, only about half of the data used were successfully recorded for Houses A and B; the remainder of the data for Houses A and B and all of the data for House C were lost because of recording instrument malfunction. Comparative plots of the calculated heat loads and the measured heat load (assuming a 0.6 heating system efficiency) are given in Figures 2-5. As shown in these figures, the calculated heat loads generally follow the trends of the measured loads. It should be noted that the indicated hourly "saw-tooth" fluctuations in measured heat load are data aberrations related to the data sampling frequency, that is, during these periods, the furnace cycle frequencies were long compared to the one hour sampling period.

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* The rates of the heat delivered to the living area to meet the heat load divided by the energy input to the heating plant.

TABLE II. SUMMARY OF ENERGY CONSUMPTION AND MEASURED AND CALCULATED HEAT LOADS

For Test Period February 8 - March 14, 1973

	Measured Electrical Kw-hr	Measured Gas Therms	Measured Heat Load, Therms System Efficiency			Calculated Heat Load, Therms
			70%	60%	50%	
House A	1955	266	186	159	133	
						175
House B	1906	273	191	164	136	
House C	1855	235	164	141	117	*

*A heat load was not calculated for the house with storm windows. However, based on the results in (1), a decrease of 13 percent would be expected, or a heat load of 152 therms.

TABLE III. LIVING ROOM TEMPERATURES AND HUMIDITIES AS RECORDED BY THE OCCUPANTS

	House A				House B				House C			
	Temperature		Relative Humidity		Temperature		Relative Humidity		Temperature		Relative Humidity	
Date	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
2/8	75	73	35	37	--	72	--	40	--	75	--	47
2/9	75	--	33	--	72	70	35	35	75	74	42	37
2/10	74	--	29	--	72	70	35	35	76	76	35	35
2/11	72	72	30	30	70	72	36	35	70	76	36	32
2/12	77	76	29	26	72	72	34	83	74	74	32	32
2/13	76	--	24	--	70	73	33	32	72	69	33	32
2/14	75	75	26	26	72	72	32	32	69	69	35	36
2/15	76	75	30	32	71	71	32	35	68	70	42	43
2/16	75	75	28	28	70	74	35	34	71	70	42	41
2/17	77	75	24	23	70	--	33	--	70	70	38	36
2/18	78	75	22	23	--	66	--	32	70	72	36	36
2/19	--	--	--	--	--	72	--	32	70	70	37	37
2/20	77	77	25	25	73	72	32	32	70	70	38	40
2/21	76	74	27	30	72	72	32	32	68	71	40	43
2/22	75	75	29	29	71	70	30	32	71	73	42	41
2/23	77	75	26	26	69	70	32	32	69	70	39	38
2/24	79	74	25	25	71	72	32	32	69	70	38	37
2/25	--	--	--	--	72	71	32	32	72	70	38	38
2/26	75	71	27	31	70	72	32	32	70	71	38	38
2/27	72	--	30	--	72	74	32	32	72	69	39	38
2/28	75	74	28	28	72	--	32	--	68	68	38	38

TABLE IV. CALCULATED HEAT LOSSES BY STRUCTURAL COMPONENT

Period - February 8 - March 14, 1973

	Walls	Windows	Doors	Ceilings	Floors	Infiltration	Total
Time Response Method Therms	59	52	0.7	8	20	54	194
Degree-Day Method*							
65 F° Therms	39	65	4	11	48	58	225
72 F° Therms	49	81	5	14	51	72	272

*Method recommended in the Handbook of Fundamentals published by the American Society for Heating, Refrigeration and Air Conditioning Engineers.

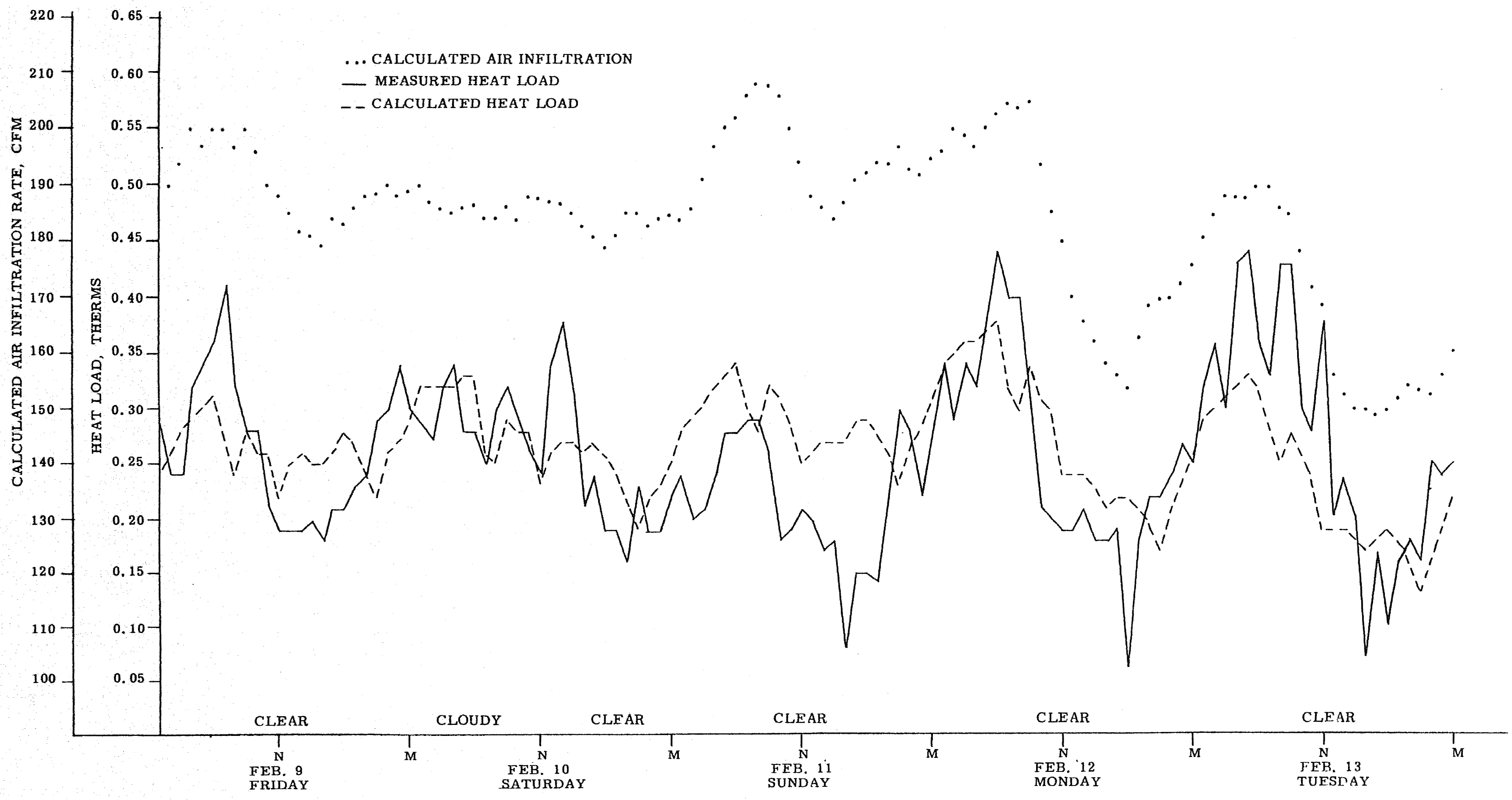

Figure 2. Hourly Load Profiles, House A, February 9 to February 13, 1973

Measured load = Measured gas consumption x 60% system efficiency.

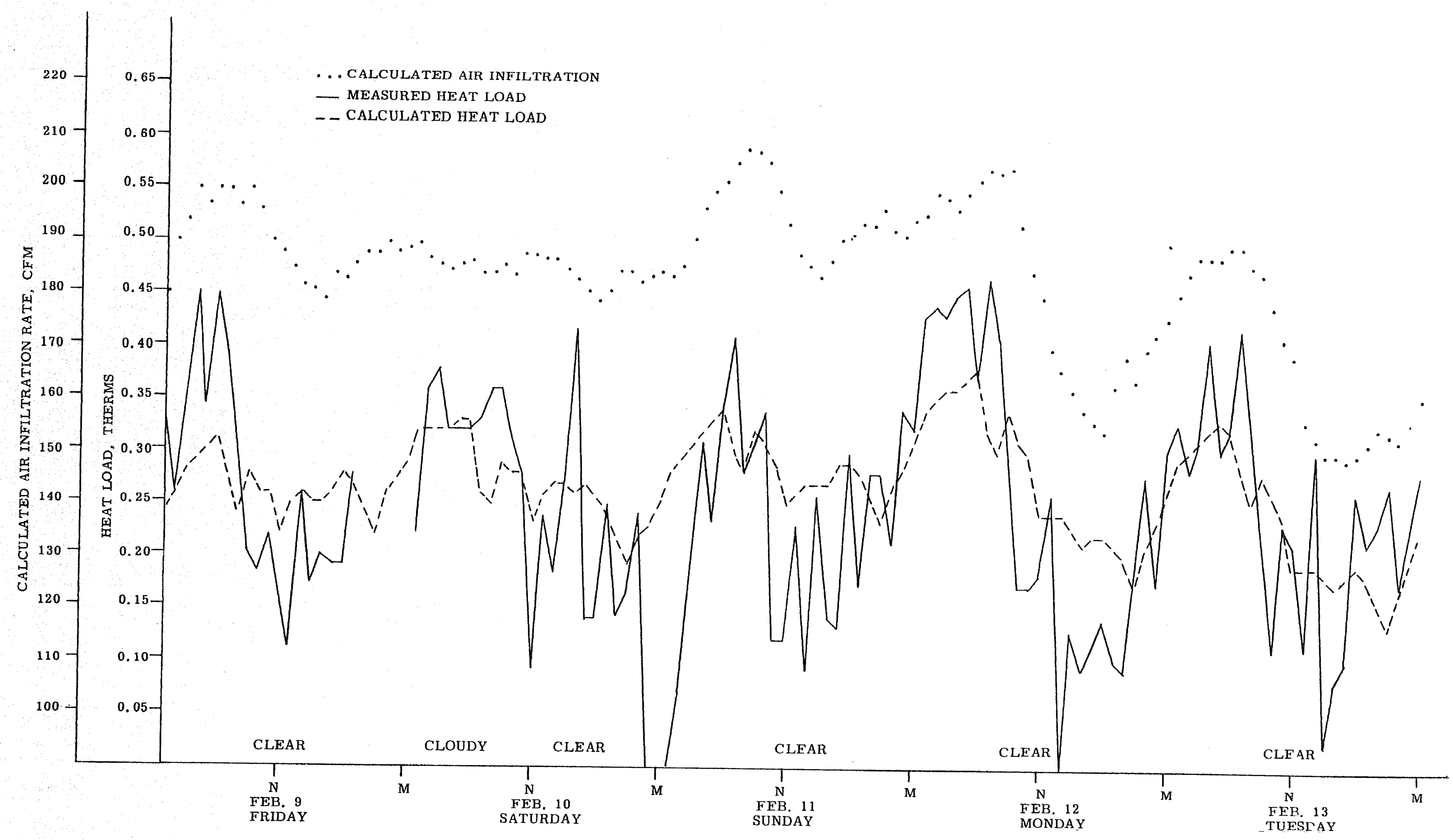

Figure 3. Hourly Load Profiles, House B, February 9 to February 13, 1973

Measured load = Measured gas consumption x 60% system efficiency.

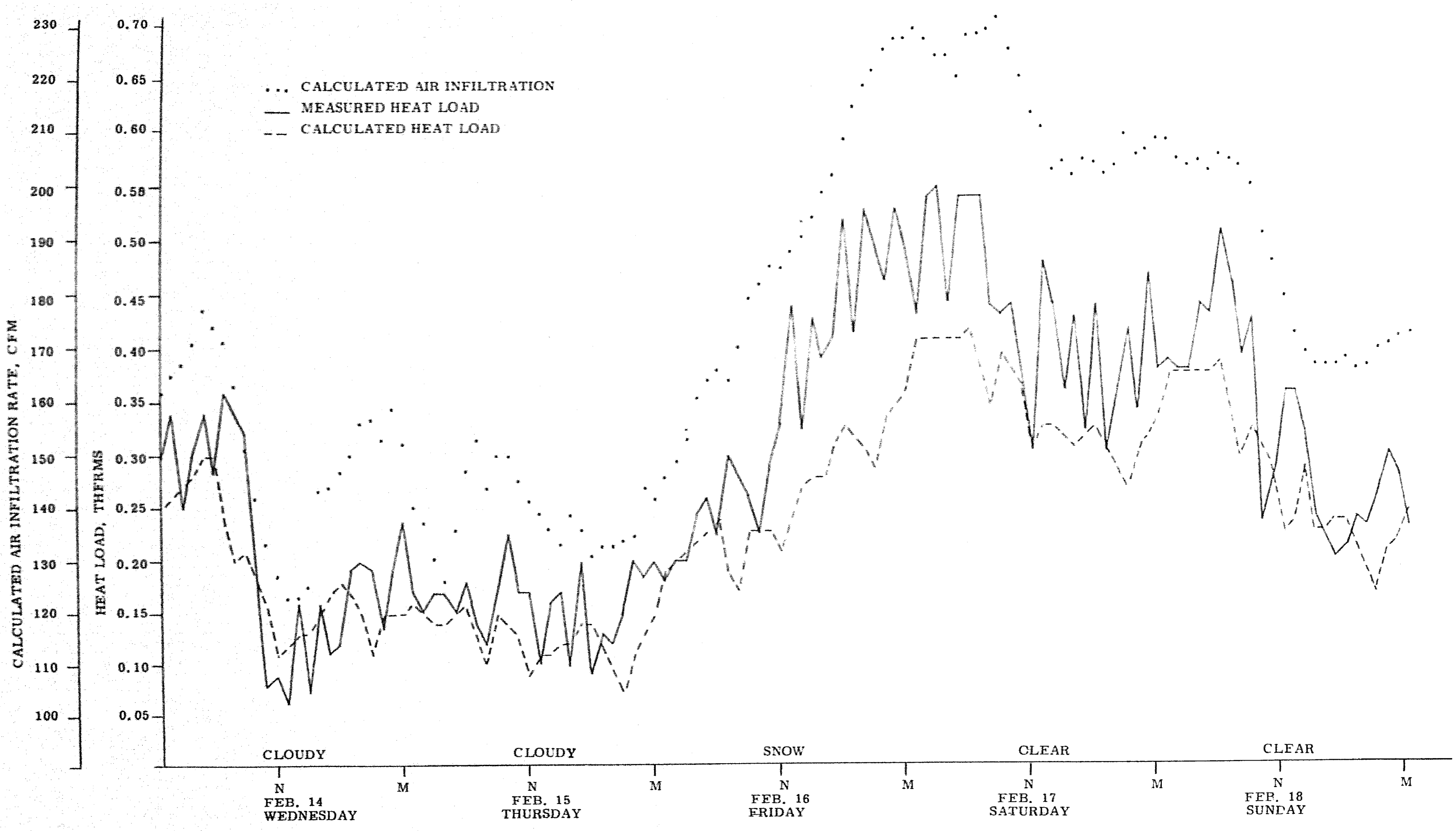

Figure 4. Hourly Load Profiles, House A, February 14 to February 18, 1973

Measured load = Measured gas consumption x 60% system efficiency.

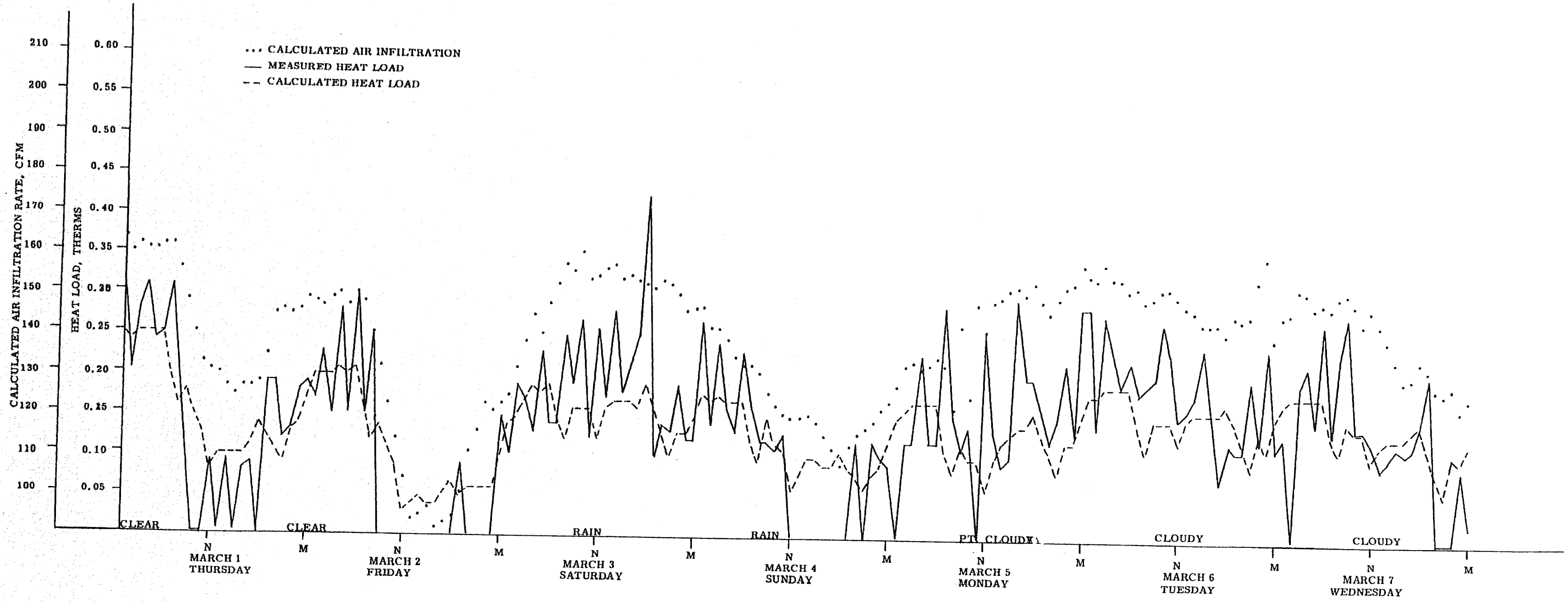

Figure 5. Hourly Load Profiles, House B. March 1 to March 7, 1973
Measured load = Measured gas consumption x 60% system efficiency.

Included with the hourly heat load data in Figures 2 through 5 are the calculated average hourly air infiltration rates. These values were calculated using a modified version of the Achenbach-Coblentz method as described in (1). These data show that both the measured and calculated heat load requirements were generally responsive to the calculated changes in infiltration rate. These results, coupled with the good agreement observed between the total measured and calculated heat loads, indicate that the infiltration model can realistically predict short term (hourly) and extended period infiltration patterns. The accuracy of such predictions has yet to be validated through comparison with experimental infiltration data.

Examination of Figures 2-5 show several marked discrepancies between the measured and calculated heat loads. The greater measured heat load on February 16, 1973 (Figure 4) coincided with a snow storm. An explanation of this discrepancy is that due to the snow, the heat transfer film coefficient on the outside house surfaces was decreased and thereby increased the heat losses. The calculation program did not adjust the film coefficient during periods of precipitation. Other discrepancies where the measured heat loads were considerably lower than calculated were probably related to "lifestyle" factors. For example, the late evening hours of Saturday, February 10, 1973 (Figure 3) showed zero consumption even though the outside temperature was 21^{o}F. A possible explanation is that there may have been a late evening party during which the greater number of occupants provided the required heat input. For other periods such as early afternoon on February 12 and 13 (Figure 3), possibly the housewife set down the thermostat and "aired" the house. Such lifestyle variables were not verified under the program.

To aid in the evaluation of the preceding data, additional data representing larger samples of residences at Twin Rivers were evaluated. Gas consumption data were obtained from the utility company for 23 "The Trent" houses at Twin Rivers for the period July 1972 to March 1973 (4). These data are summarized in bar chart form in Figure 6. Since the furnace was the only gas consuming appliance in these houses, the data represent relative heating requirements.

As shown in Figure 6, the heating requirements for the 23 houses ranged approximately + 25 percent about the median. The three test houses, A, B, and C were within the 951-1000 therm interval and were representative of "average" consumption levels. Similar gas and electric consumption data were obtained for 152 town house units at Twin Rivers for the July 1972 to March 1973 time period (2). Correlation analysis of these data with structure and occupant factors identified no items having a strong correlation with gas consumption except for house size. Items evaluated included: house orientation, installation of storm windows, electrical consumption, number of occupants, and family income. The

interpretation placed on the results of these correlation analyses does not preclude that such factors as orientation or storm windows have no effect on heating load, but rather that other, as yet unidentified, variables can have a sufficiently large effect so as to overshadow factors such as house orientation and application of storm windows. Possible unidentified variables could be divided into two groups: Occupant lifestyle variables, and construction related variables. Examples of probable lifestyle variables would be: Thermostat set-point temperature; night set-back of the thermostat; opening of bedroom windows at night; airing the house; use of major appliances and lights; use of window drapes and shades; and use of ventilation fans. Similarly, probable construction related variables would primarily be those associated with the quality of workmanship of components, (e.g., windows or patio door assemblies), and of the house structure (e.g., proper installation of insulation, the caulking of cracks, and the fitting of doors and window frames). Therefore, in evaluating the observed close agreement between the measured and calculated heat load values as shown in Table II and in Figures 2 through 5, this degree of agreement would be valid only for houses having some "average" combination of unidentified lifestyle and construction variables.

Although House C, the only house equipped with storm windows, had the lowest heating energy requirement of the three houses, it cannot be concluded from these data that the lower energy requirement was the direct result of the installed storm windows. Although such a reduction of energy would be expected, the data obtained from Figure 8 indicates that the magnitude of other unidentified variables prohibits the quantification of a single factor such as storm windows.

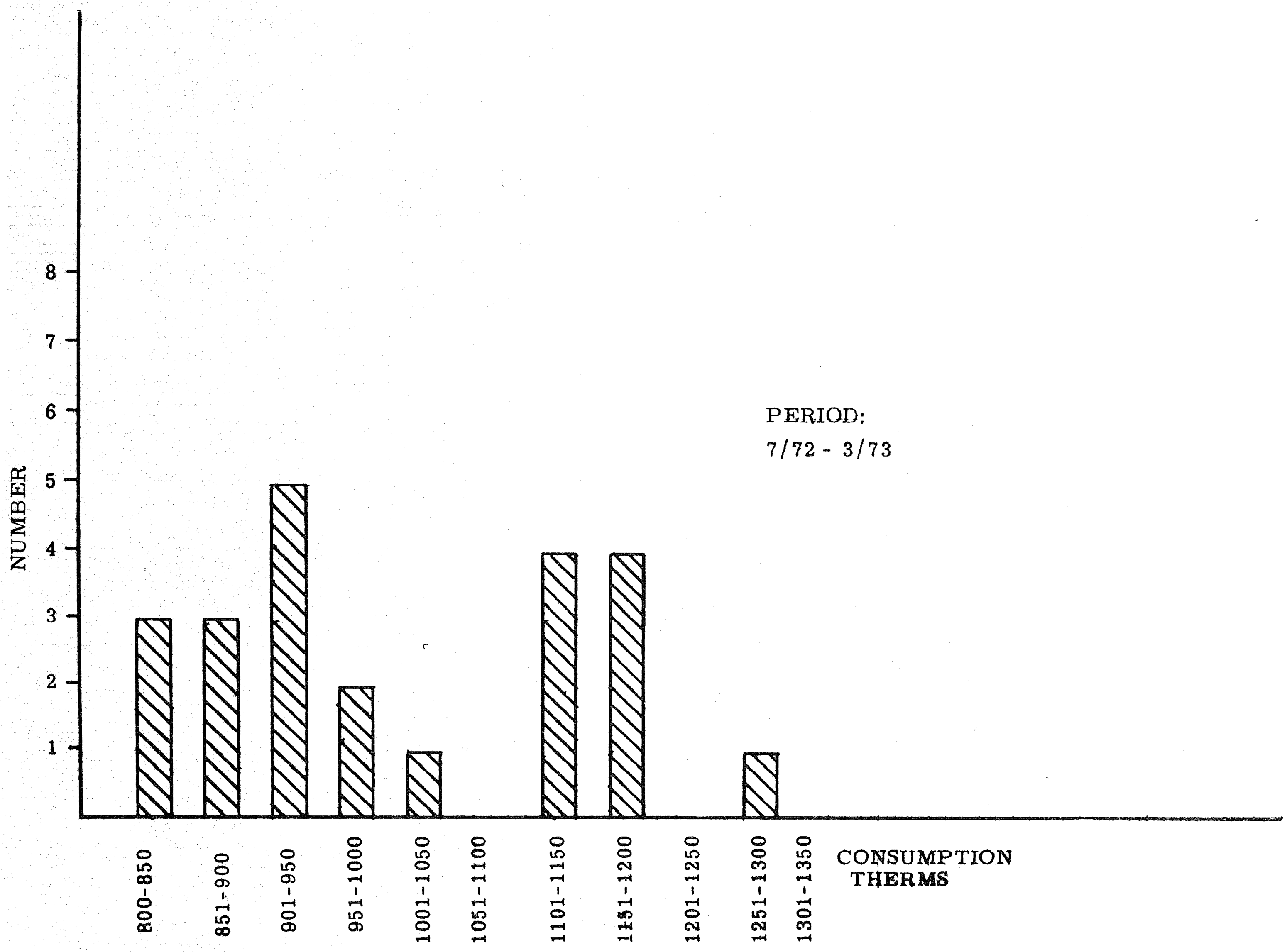

Figure 6 Relative Heating Gas Consumption of 23 "The Trent" Houses

REFERENCES

1. Residential Energy Consumption - Single-Family Housing Final Report. HUD-HAI-2, March 1973.

2. Energy Utilization in a Residential Community. R.A. Grot and R.H. Socolow, Working Paper W-7, Princeton University Center for Environmental Studies, February 20, 1973.

3. ASHRAE Handbook of Fundamentals. The American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. New York, New York, 1967.

4. Private Communication, R.A. Grot, Princeton University.

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